Qingshan XU[1], Qiuqi ZHU[1], Haixiang ZANG[1], Xiaodong YUAN[2]

Jiangsu Provincial Key Laboratory of Smart Grid Technology & Equipment,,Southeast University, China (1),
Electrical Power Research Institute (EPRI) of Jiangsu, China (2).

A Rigorous Method for Power Quality Evaluation of High-speed Railway Using Electrical Transient Analyzer Program

***Abstract**. A rigorous method is introduced to evaluate the overall impact of high-speed railway (HSR) traction loads on a power system using the electrical transient analyzer program (ETAP) platform (Operation Technology, Inc, USA) in this paper. By establishing the detailed models of network elements and the general traction substation model with the powerful simulation software, this method is capable of handling the large-scale power systems and the various transformer connection schemes. As the interaction between the power system and the traction power-supply system is considered, the negative sequence components and harmonics effects can be estimated in detail both at the points of common coupling (PCCs) and in public grid. Shanghai-Nanjing intercity railway is taken for an example, in which four power quality indices are simulated and evaluated in different operating conditions. By the comparison of simulation data and measured data, the proposed method is verified to be credible and feasible for the power quality evaluation in practice.*

***Streszczenie.** W artykule opisano sposób ścisłej oceny wpływu trakcji elektrycznej kolei dużych prędkości na system energetyczny. W badaniach symulacyjnych wykorzystano platformę z analizatorem stanów przejściowych sieci (ang. Electrical Transient Analyzer Program). (**Metoda ścisłej oceny jakości energii w kolejach dużych prędkości analizatorem ETAP**)*

Keywords: high-speed railway (HSR); negative sequence components; harmonics; electrical transient analyzer program (ETAP).
Słowa kluczowe: Kolej dużych prędkości, składowa przeciwna, harmoniczne, analizator ETAP.

1 Introduction

Recently, high-speed railway (HSR) has rapidly developed in China and the power quality issue is becoming increasingly serious. Poor power quality may significantly affect the operation of the power system and other connected equipments. As usually using the single-phase power supply, the railway system generates lots of negative sequence components to the public grid. These negative sequence components may lead to additional loss and overheating of motors, undesired tripping of relays, etc. [1,2]. A large amount of harmonics are also generated by traction drivers into the grid, which may lead to torque pulses and torque drops of rotational machines, extra temperature rise of equipment, vibrations of power capacitor banks and protectors, etc. [3,4]. Compared to the conventional electrified railway, the high-speed electrified railway has a higher traffic density, which requires more reliable and larger traction power [5]. Furthermore, its effects have new characteristics, such as the greater negative sequence components and the wider harmonic spectrum. As the HSR traction substations along a railway route are usually fed by the high-voltage network directly, its effects on the public grid need to be paid special attention.

Many works have been undertaken for power quality evaluation of traction loads [6-8]. Although these methods are quick and straightforward, they are somewhat not rigorous. These methods are limited to estimate the effects at the points of common coupling (PCCs) without considering the penetration in the public grid. In addition, the impact of traction loads cannot be decided by these simple methods alone for it is caused not only by traction loads but also by other disturbance sources in grid. Furthermore, the interactions between traction loads of different substations are also significant, especially for the neighbouring substations. To estimate the power quality effects, the comprehensive simulation of the whole system that is composed of the power system and the traction power-supply system is indispensable. And the interaction between these two systems should be taken into consideration. Thus, the detailed component models, including the models of network elements and the traction substation model, must be established appropriately. Moreover, a advanced system analysis capability is needed for the rigorous study of the effects, thus, a powerful simulation tool should be used to satisfy the requirements of the rigorous system analysis. As a result, the detailed component models and the suitable simulation tool are predominantly concerned in the evaluation work.

The effects of the negative sequence components and harmonics are estimated in detail both at the PCCs and in the public grid in this paper. The electrical transient analyzer program (ETAP) software (Operation Technology, Inc., USA) is chosen as the analysis tool since it is powerful in the field of power system analysis, especially for the unbalance analysis and the harmonic analysis. All network elements, including generators, transmission lines, transformers and loads, are modelled in detail in this paper, and, a general traction substation model based on the principle of equivalent transformation is adopted. These make the proposed method be capable of handling large-scale power systems and various transformer connection schemes. In this paper, Shanghai-Nanjing intercity railway was surveyed and taken for case study. The evaluation work in this paper covers four power quality indices, including unbalanced three-phase voltages, negative sequence current injections into nearby generators, harmonic current injections and harmonic voltages at the PCCs. Additionally, the simulation results are compared with the practical measured data to verify the efficiency of the proposed evaluation method.

2 System model

As the fundamental information of the evaluation, the three-phase power flow results, such as voltages on each bus and currents of each branch in the power system must be firstly calculated, then, the further assessment can be undertaken. Therefore, a detailed model of the whole system that is composed of the public power system and the traction power-supply system should be established. In this section, the power system model is firstly introduced, followed by the traction power-supply system model.

2.1 Power system model

For the unbalance analysis and the harmonic analysis of a high-voltage network with HSR traction loads, the asymmetry, nonlinearity and frequency characteristics of the power system components must be recognized. All detailed network component models, including generators, transmission lines, transformers and loads, are completely provided on the ETAP platform. Given the required data for the unbalance analysis and the harmonic analysis, these existing models can be directly applied in this study. The primary considerations for the data requirements of network component models are briefly presented as following

1) Generators: In the generator model, the internal sequence impedances are adopted to describe the inherent generator phase unbalance resulting from the system unbalance. At the harmonic frequencies, the equivalent impedance of a generator approaches its negative sequence impedance. Thus, the sequence impedance data are required for the generator model.

2) Transmission lines: Transmission line is represented by a multiphase coupled model in which the data of positive, negative and zero sequence impedance and admittance are needed. Harmonic impedance of a transmission line is determined by the impedance at the fundamental frequency considering the adjustments cause by harmonic frequencies.

3) Transformers: 2-winding and 3-winding transformers are included in this paper. The copper and core losses, the off-nominal tapping, the phase shift and so on are considered in the models. And, the positive and zero short circuit impedance, the winding connections and the grounding type are included in the concerned transformer data. Also, the resistance and inductance components of the transformer short circuit impedance are frequency-dependent.

4) Loads: The balanced loads in grid which are composed of constant impedance, constant current and constant power components are represented by the polynomial models. If not producing the harmonics, the equivalent harmonic impedance of the load can be determined by its basic load.

2.2 Traction power-supply system model

Several transformer connection schemes are commonly used in HSR substations, such as single-phase, V-V, Scott, Le-blanc, Wood-bridge, and YNd11. Each connection scheme has its own properties, which result in different effects on the power system. Both accurate and simplified models for the traction substations have been completely developed and been used for the evaluation [9,10]. In order to accommodate to all transformer connection schemes, a general method based on the principle of equivalent transformation is utilized here [11]. The traction transformer is considered as a multi-port network as shown in Fig. 1. Each traction arm of the substation is viewed as one port.

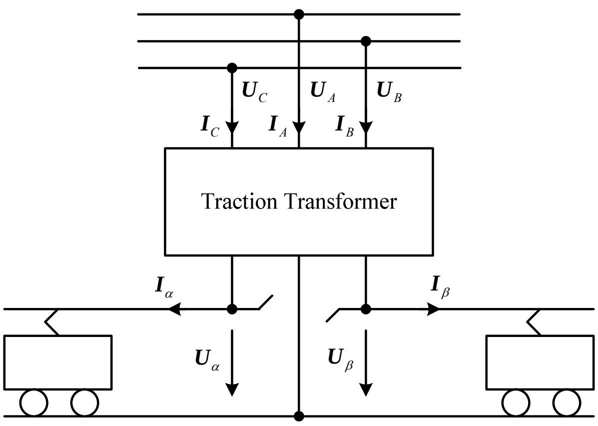

Figure 1. Traction transformer port model

In this model, the transformer is assumed to be ideal. Therefore, no impedance is included in the transformer and, as a result, no voltage drop and loss are incurred. Besides, the three-phase system at the primary side is assumed to be symmetrical. The a-phase voltage is selected as the reference voltage.

The voltage and the current of the port p ($p=\alpha, \beta$) of the secondary side are shown as following

(1) $$\boldsymbol{U}_p = U_p e^{-j\psi_p} = \sqrt{3} U_A K_p e^{-j\psi_p}$$

(2) $$\boldsymbol{I}_p = I_p e^{-j(\psi_p + \varphi_p)}$$

where, U_p is the voltage of port p; I_p is the load current of port p; K_p is the ratio of traction port voltage and the primary line voltage; ψ_p, which is defined as the connection angle of port p, is the lagging phase angle of $\boldsymbol{U}_p$ to $\boldsymbol{U}_A$; φ_p is the power factor angle of current $\boldsymbol{I}_p$ lagging to voltage $\boldsymbol{U}_p$ at port p.

When a port at the secondary side works independently, no zero sequence is included at the primary side. Thus, three-phase currents caused by port p satisfy

(3) $$\boldsymbol{I}_{Ap} + \boldsymbol{I}_{Bp} + \boldsymbol{I}_{Cp} = 0$$

Consider the power balance equation for the two sides of the traction transformer

(4) $$\boldsymbol{U}_A \bullet \boldsymbol{I}_{Ap}^* + \boldsymbol{U}_B \bullet \boldsymbol{I}_{Bp}^* + \boldsymbol{U}_C \bullet \boldsymbol{I}_{Cp}^* = \boldsymbol{U}_p \bullet \boldsymbol{I}_p^*$$

Combining equation (1) - (4), $\boldsymbol{I}_{Ap}$, $\boldsymbol{I}_{Bp}$, $\boldsymbol{I}_{Cp}$ can be solved easily. By the superposition principle, when all ports work, the total three-phase currents at the primary side can be achieved as

(5) $$\begin{bmatrix} \boldsymbol{I}_A \\ \boldsymbol{I}_B \\ \boldsymbol{I}_C \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 0 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ \sum_{p=\alpha,\beta} K_p \boldsymbol{I}_p e^{-j\psi_p} \\ \sum_{p=\alpha,\beta} K_p \boldsymbol{I}_p e^{j\psi_p} \end{bmatrix}$$

where, a equals to $e^{j2\pi/3}$.

Then, the currents in equation (5) are transformed to three-phase power load to simulate the unbalance characteristics of traction loads. Multiplying the harmonic current content ratio of locomotives by the currents in equation (5), the traction substation can be constructed as a harmonic current source.

The traction substation model above based on the principle of general equivalent transformation can be applied to all transformer connection schemes. According to the connection angles, the commonly used traction transformers can be classified into two groups. For some connection schemes, such as V-V and YNd11, the connection angle difference of two traction ports is 120°. While for other connection schemes, such as Scott, Le-blanc and Wood-bridge, the connection angle difference is 90°.When the connection angle is determined, the general model is specified and can be applied in this study.

3 Case study

A case study using Shanghai-Nanjing intercity railway system is presented in this section to demonstrate the efficiency of the proposed method in estimating the overall impacts on the power system with HSR loads. Shanghai-Nanjing intercity railway is the first high-speed electrified railway directly connected to 220kV voltage level in Jiangsu Province. 5 traction substations are included along the railway route, namely, Baohuashan, Danyang, Changzhou, Wuxi East and Kunshan. V-V connection transformer is adopted by all these substations and each substation is supplied by two independent incoming feeders from 220kV high-voltage grid. 229 generators, 932 transformers and 1345 transmission lines are contained in the 220kV network of Jiangsu Province.

The degree of power quality effects caused by HSR traction loads depends on the electric locomotive type, the traction transformer connection schemes, the trains' movements, etc.. Under different conditions, the load currents of two traction arms are very different. In this section, three typical scenes are reviewed for the power quality issue of the railway as following

1) Scene 1: currents of heavy load arm and light load arm are calculated by RMS.

2) Scene 2: currents of heavy load arm and light load arm are respectively calculated by 95% RMS and RMS.

3) Scene 3: currents of heavy load arm and light load arm are respectively calculated by maximum and RMS.

Namely, the normal, 95% probability and maximum operation conditions of the railway are respectively taken into consideration. And, the load currents of traction substations are obtained by the field measurement. Four power quality indices of the evaluation of negative sequence components and harmonics are respectively discussed in this section.

3.1 Unbalanced three-phase voltage at the PCCs

In order to reduce the negative sequence components effects caused by HSR loads, the arrangement of the exchange phase between traction substations (i.e., substations in succession are fed on different phases alternatively) are usually adopted by the railway departments. Thus, the traction load is almost equally distributed in the three-phase. According to GB/T 15543-2008, the unbalance degree of three-phase voltage is permitted to be no more than 2% in normal situation. The simulation values and measured values of voltage unbalance degree at the PCCs are listed in Table 1.

Table 1.Three-phase voltage unbalance degree at the PCCs [%]

PCC	Simulation value			Measured value	
	Scene 1	Scene 2	Scene 3	Average	95%
Dongyang	0.228	0.250	0.293	0.171	0.238
Yuheng	0.320	0.369	0.432	0.270	0.384
Dongqing	0.304	0.320	0.337	0.104	0.175
Xiangnan	0.341	0.347	0.387	0.263	0.358
Shipai	0.108	0.126	0.126	0.073	0.122

As can be seen from the above table, three-phase voltage unbalance degree at each PCC is within the safe limit. The greatest value of unbalance degree appears in scene 3, followed successively by scene 2 and scene 1. In scene 1, the greatest voltage unbalance degree, up to 0.341%, occurs at Xiangnan caused by Wuxi East substation. In the other two scenes, the voltage unbalance degree at Yuheng caused by Danyang substation is greatest, which reaches to 0.369% and 0.432% respectively.

The operating condition of scene 2 is consistent with that of 95% probability measurement level. As shown in table 1, these two sets of data are very close except at Dongqing affected by Changzhou substation, which confirms the validation of the proposed evaluation method.

3.2 Negative sequence current injections into nearby generators

In general, HSR traction loads are connected to high-voltage level on the public power system to increase the short-circuit capacity at the PCCs and therefore reduce the unbalance effect. However, this makes substations so electrically close to the generators in power system that more concerns are attracted for the excessive negative sequence current injections into nearby generators [12].

The maximum negative sequence current allowed of synchronous generator is provided in GB755-2008. In continuous operation, the negative sequence current I_1 should be less than 8% of rated current I_N. Several power plants nearby the HSR route are selected and the equivalent negative sequence current injections are computed. Table 2 shows the simulation values under the severest circumstance (scene 3).

Table 2. Maximum negative sequence current injections into nearby power plants

Power Plant	Capacity [MW]	Equivalent I_N [A]	Equivalent I_1/I_N [%]
Jinlingranmei	1000	1187.721	0.096
Jinlingranji	2*390	1174.828	0.061
Zhenchang	2*137.5+2*140	405.093	0.785
Zhenchang 2	2*630	733.920	0.159
Jianbi	4*330	916.271	0.528
Jianbi 2	2*330+1000	903.602	0.972
Changzhou	2*630	1673.489	0.540
Ligang 2	2*600+2*630	733.502	0.254
Wangting 2	2*630	1674.370	3.853
Wangting	310+320+2*390	1030.471	0.184
Changshu 2	3*650	800.552	0.280

As can be seen from Table 2, the percentages of the equivalent negative sequence current are all less than 1% in scene 3. Wangting 2 whose percentage is up to 3.853% is affected most severely. It should be noted that the maximum load condition at each PCC does not certainly occur at the same time. Consequently, the simulation results shown in Table 2 are comparatively conservative.

Generally speaking, the ability of a generator to withstand the negative sequence current is proportional to its capacity. Besides, the closer the electrical distance between traction substation and generator is, the severer the negative sequence effect is. For those PCCs whose unbalance degree is very low due to high short-circuit capacity (i.e., very electrically close to some generators), special attention should be paid to the possible excessive negative sequence current injections into nearby generators.

3.3 Harmonic current injections into the power grid

According to GB/T14549-93, the harmonic current injections into PCCs from all users should be restricted within allowed limits, however, the allowed values can't be used for assessment directly. Firstly, they should be converted by the ratio of the actual short-circuit capacity and the reference short-circuit capacity. Secondly, they should be distributed by the ratio of the user's protocol capacity and the power supply capacity at that point. Fig. 2 shows the harmonic current injections into power system from Wuxi East substation in 3 scenes. The simulation results and the allowed values of several characteristic harmonic currents are listed in Table 3.

It can be seen from Fig. 2 and Table 3 that the harmonic currents in scene 3 are highest, but still not exceeding the allowed value. Comparing the harmonic currents of all orders, 3rd, 5th, 7th, 11th, 13th and 37th ones are relatively predominant. Since pulse width modulation (PWM) technology has been applied in Shanghai-Nanjing intercity railway, its harmonic characteristics differs from that of conventional electrified railway in which the AC-DC type electric locomotives are generally used. On one hand, low-order harmonic components are greatly reduced; on the other hand, the harmonic spectrum range becomes wider and the high-order harmonic components increase obviously.

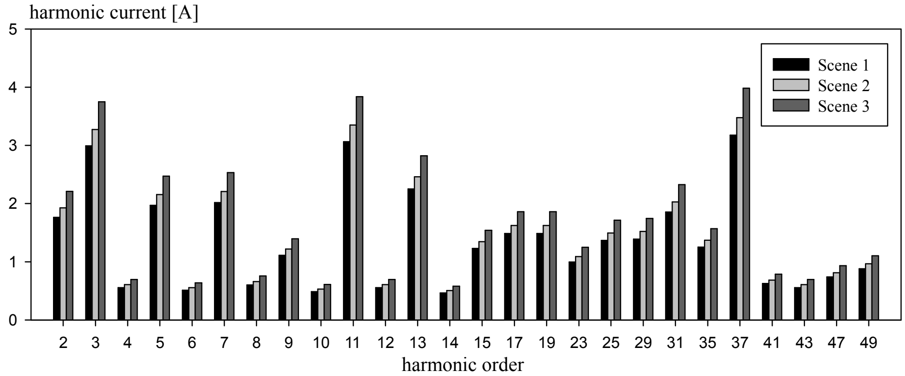

Figure 2. Harmonic current injections from Wuxi East substation

Table 3. Harmonic currents injected from Wuxi East substation [A]

Harmonic order	3	5	7	9	11	13	17	19	25
Limit	7.012	8.341	7.768	5.993	7.084	6.521	5.239	4.681	3.557
Scene 1	2.991	1.970	2.024	1.110	3.063	2.254	1.488	1.487	1.370
Scene 2	3.269	2.163	2.208	1.217	3.353	2.458	1.623	1.622	1.503
Scene 3	3.753	2.469	2.530	1.402	3.839	2.819	1.861	1.861	1.717

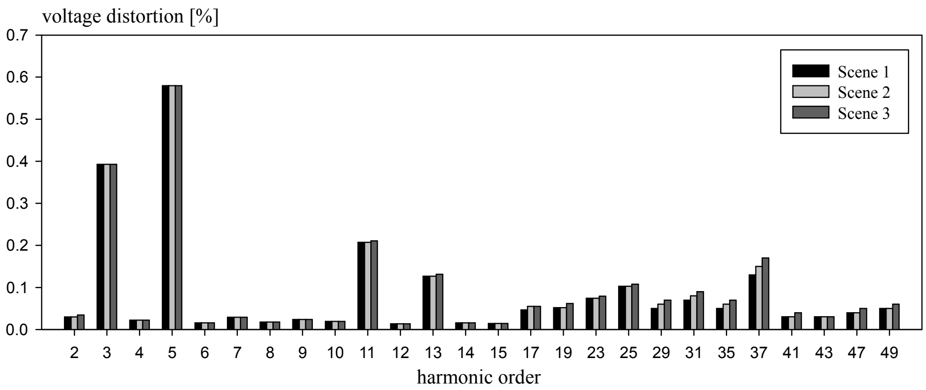

Figure 3. voltage IHD on Xiangnan bus

Table 5. voltage IHD and THD on Xiangnan bus [%]

Harmonic order		3	5	11	13	17	19	23	25	THD
Simulation Value	Scene 1	0.393	0.580	0.207	0.127	0.046	0.052	0.075	0.103	0.767
	Scene 2	0.393	0.580	0.207	0.127	0.055	0.052	0.075	0.103	0.774
	Scene 3	0.393	0.580	0.210	0.131	0.055	0.062	0.079	0.108	0.788
Measured Value	Average	0.351	0.502	0.290	0.142	0.027	0.013	0.066	0.071	0.719
	95%	0.383	0.577	0.325	0.165	0.039	0.024	0.073	0.080	0.773

3.4 Harmonic voltages at the PCCs

According to GB/T14549-93, the limits of harmonic voltage distortion in public grid are listed in Table 4. It should be noted that the standard of 220kV voltage level applies to the one of 110kV level.

Table 4. Public grid harmonic voltage limits

Standard voltage [kV]	THD [%]	IHD [%]	
		Odd	Even
110	2.0	1.6	0.8

By harmonic analysis, the voltage individual harmonic distortion (IHD) and the total harmonic distortion (THD) at the PCCs can be achieved easily. Fig. 3 shows the voltage IHD on Xiangnan bus connected to Wuxi East station. Besides, simulation data and practical measured data of several characteristic harmonics are compared in Table 5.

Obviously, the voltage THD at each PCC is less than 2%, the voltage IHD of each odd order is below 1.6% and the IHD of each even order is below 0.8%. Thus, the national standard requirements of harmonic distortion indices are fulfilled.

Although the harmonic values of all orders increase from scene 1 to scene 3, they are very close in each scene especially at low-orders. And, the voltage IHDs of odd-orders, such as 3^{rd}, 5^{th}, 11^{th}, 13^{th} and 37^{th} are high. It can also be observed that the harmonic voltage spectrum is wide and high-order harmonic components are great, which coincides with the conclusions drawn above.

The simulation data in scene 2 is in accordance with the measured data of 95% probability at the characteristic orders such as 3^{rd}, 5^{th}, 11^{th}, 13^{th}, 23^{rd} and 25^{th}, which verifies the efficiency of the proposed evaluation method again.

4 Conclusion

A method was presented in this paper, capable of evaluating the overall impacts on a power system with HSR traction loads. Based on the powerful simulation capability of ETAP platform, the method can handle the large-scale power system with numerous network elements. Besides, it is possible to deal with the various transformer connection schemes by adopting the general model of traction substation. By using this method, both the effects at the PCCs and the penetration in the power system can be evaluated with sufficient accuracy.

With the significantly increasing demand for power of HSR traction systems, it is critical that an in-depth impact evaluation for these special loads be performed by power companies. A feasible solution to this problem is presented in this paper, and it has a significance of being referenced and improved for further study.

REFERENCES

[1] Antonio D.A., Maria M., Vito G.M., Pericle Z., New Power – Quality Assessment Criteria for Supply Systems Under Unbalanced and Nonsinusoidal Conditions, *IEEE Transactions on Delivery*, vol.19, no.3, July 2004, 1284-1290

[2] Golovanov N., Lazaroiu G.C., Roscia M.; Zaninelli D, Voltage Unbalance Vulnerability Areas in Power Systems Supplying High Speed Railway, *Power Engineering Society General Meeting*, San Francisco, CA, USA, June 2005

[3] Peechin T., Pohchiang L., Donaldgrahame H., Optimal Impedance Termination of 25-kV Electrified Railway Systems for Improved Power Quality. *IEEE Transactions on Power Delivery*, 2005, 20, 1703 - 1710

[4] Petere S., Marek W., Markf M., System Impacts Evaluation of a Single-phase Traction Load on a 115-kV Transmission System. *IEEE Transactions on Power Delivery*, 2006, 21, 837-844

[5] Yuquan L., Guopei W., Huangsheng H., Li W., Research for the Effects of High-speed Electrified Railway Traction Load on Power Quality. *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Weihai, China, July 2011

[6] Shaofeng X., Qunzhan L., A Practical Method for Assessment of Harmonic Emission of Electrified Railway, *IEEE Industrial Electronics Society*, France, November 2006

[7] Wenshyan C., Jyhcherng G., Binkwie C., Sanyi L., New Criteria for Estimating Voltage Unbalance Due to Special Connected Transformers in High Speed Railway Systems, International Journal of Emerging Electric Power Systems, vol.4, no.1, 2005

[8] Haiqun W., Yingjie T., Qinchang G., Evaluation of Negative Sequence Current Injecting into the Public Grid from Different Traction Substation in Electrical Railways. *International Conference and Exhibition on Electricity Distribution*, Prague, Czech Republic, June 2009

[9] Chengping H., Chijui W., Yungsung C., Shihkai P., Jungliang Y., Minghong H., Loading Characteristics Analysis of Specially Connected Transformers Using Various Power Factor Definitions. *IEEE Transactions on Power Delivery*, vol.21,no.3, July 2006, 1406 - 1413

[10] Mohsen K., Mohammad J.S., Siamak F., Seyed S.F., Modeling and Comparison of Tranction Transformers Based on Utilization Factor Definitions, *International Review on Modelling and Simulations*, vol.4, no.1, February 201, 342-351

[11] Qunzhan L., Power Supply and Compensation Analysis for Traction Substation, *Beijing: China Railway Press*, 2006

[12] Shilin C., Rayjong L., Paohsiang H., Traction System Unbalance Problem – Analysis Methodologies, *IEEE Transactions on Power Delivery*, vol.19, no.4, October 2004, 1877-1883

***Authors**: Dr. Qingshan Xu works in School of Electrical Engineering, Southeast University, Nanjing, China, 210096, Email: xuqingshan@seu.edu.cn; Qiuqi Zhu studies in School of Electrical Engineering, Southeast University, Nanjing, China, 210096, Email: autqisky@126.com; Haixiang Zang studies in School of Electrical Engineering, Southeast University, Nanjing, China, 210096, Email: zanghaixiang@seu.edu.cn; Xiaodong Yuan works in Electrical Power Research Institute of Jiangsu, Nanjing, China, 211103, Email: lannyyuan@hotmail.com.*